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RES diffusion and R&D investments in the flexibilisation of the European electricity networks

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ABSTRACT

The present analysis adds up to the discussion carried around the flexibilisation of the electricity networks, as means of higher diffusion of renewable energy sources (RES). Inspiring from innovation studies the paper proposes an economic rationale for considering RES technology manufacturers as investors in electricity networks. Moreover, the present analysis scrutinize the extent to which the various economic operators within specific segments of the power supply chain invest in a portfolio of research and development activities, among which the electricity grids and storage technologies. The intensity of these research investments was mapped across the European countries for the year of 2011. Their geographic distribution confirms the rationale of an analysis based on canonical correlation testing the associations between RES market diffusion and power network indicators. The analysis provides useful insights for specific technology, such as the one revealing PV market sensitivity to research investments in storage technologies, confirming a potential business model coupling the two technologies. Accommodating this pattern and enabling further diversification of research portfolios, the public incentives could be redesigned in order to address the flexibilisation of power networks.

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Appendix E. Correlation matrix for matrix and network variables defined as: 1-Installed capacities by specific technology (wind or PV); 2 - Feed in Tariffs by country for specific technology (wind or PV), 3- Corporate research in electricity grids ;4-orporate research in storage technologies;5- Share wind curtailment in total electricity available for consumption ;6- Network Length 1080
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1. Introduction

Renewable energies are increasingly considered as key sources enabling environmental sustainability and thus encouraged to occupy an important place in the energy system [1–3]. The diffusion of RES should ensure from the risks of volatility of fossil prices or of geopolitical pressures [4–8]. However, in the long-run, the penetration of RES necessarily would imply a process of adaptation and change of the existing infrastructure, because of RES' intrinsical features, such as intermittency and variability. The increasing needs of balancing intermittent RES, intertwined with the design of long term changes of the electricity mix, would likely affect both distribution and transmission power networks. For example, major substitution effects could derive from the process of total decommissioning of nuclear facilities announced for Germany [9], Switzerland [10] or a progressive phase-out reducing the country's reliance on nuclear energy in the case of France [11]. In this context, a change in the merit order of power generation options, stemming from a higher contribution of RES, would require network updates. In fact, German government's phase-out strategy was accompanied by plans for a larger integration of renewable energy sources achievable through an upgrade and expansion of its electricity grid over the next decade [12]. Increased capacity of power system transmission and distribution lines (e.g. HVAC or HVDC technologies) could act as enablers of grid flexibility [13].

The need for network investments has been examined by electricity market studies [14–16]. According to these studies, the main actors, i.e. system operators, would chose to invest in grids enhancements in order to avoid curtailments or costly balancing transactions. The investment decision usually was associated with regulated actors situated in the *lower segment* of the supply chain, such as TSOs or DSOs. Their rationale of investment pertained to the avoidance of congestion, but also to exploitation of intra-regional differences in cost [14]. Accordingly, a regulated firm would have interest in reducing congestion, whereas a profit maximizing utility could become monopolist of residual demands left unserved by intra-regional imports [14].

The present work adds up to the general discussion, considering that the investment decision in electricity networks could be initiated by unregulated actors situated in the *upper segments* of the supply chain, such as *manufacturers of RES technologies*. In other words, among the bundle of stakeholders aiming at stimulating the network modernization, the RES technology manufacturers may have a prominent role. Their rationale of investment in the modernization of the network would target increased capacity/flexibility of the electricity network, as means of obtaining higher returns from RES activities, and mid-term benefits such as an expansion of their market potential. Moreover, depending on future plans for an accelerated diffusion [2], RES integration would likely carry an important pressure on the local energy system.

This hypothesis was lesser investigated and the current analysis aims at filling in this gap. More specifically, we aim at corroborating the hypothesis that the system adequacy and the technological constraints of the existing infrastructure play a crucial role for the successful deployment of RES. We consider as well that the evolution of the role of grid adequacy should not be assumed according to a reductionist approach. It is determined, in our view, as the result of simultaneous actions, feedbacks and complementarity relationships that are structured amongst different players along the whole supply chain. The paper tries to empirically ground this hypothesis. We checked for the presence of statistical association between two sets of indicators. One referred to the RES market performance, and the other is concerning the physical adequacy and the flexibility of the network, across a sample of countries in the EU. The conceptual framework of the present analysis is inspired from diffusion models of wind technologies [17] and regional studies [18].

The paper is organized as follows: after the introduction, the Section 2 describes the main findings on drivers of investments from a literature review. The Section 3 presents a theoretical formulation that includes incentives for RES firms to invest in the adequacy and flexibility of the network. The Section 4 describes the data and the Section 5 offers evidence of growing importance of variable energy sources and research investments in the network across European countries. The results are presented in the Section 6 and further discussed in Section 7. Finally, the last section concludes.

2. Investment decision and actors responsible for the flexibilisation of electricity networks

The liberalization of the electricity markets in EU has allowed a horizontal restructuring of the power generation segment, a vertical separation of the supply chain (i.e. generation, transmission and distribution of power) and the creation of wholesale spot energy and operating reserve market [19]. This process had important consequences pertaining to both market structure and market mechanism.

Concerning the market structure, the liberalisation enabled an ongoing increase in the number of distributed producers, further empowering renewable energy industries to develop. These latter have been particularly encouraged to ensure a significant contribution, i.e. 20% of energy consumption by 2020 [1] and 27% of energy consumption by 2035 [2]. The diffusion of RES has changed the vertical and horizontal relations in the supply chain, favouring also the emergence of competition among generators in different locations. However, for system operators the intensity of competition could be delinked from the local transmission capacity, since they can avoid congestion with output restriction [14]. On the contrary, the RES producers might not exhibit the same strategy as the regulated actors and, consequently choosing a profit maximization over a cost minimization strategy. Consequently, the transportation capacity, as basis for competitive advantages, might carry a significant importance for the RES producers rather than for the system operators.

The difference in investment behavior between the two set of actors relate also to the diversity of drivers of investment decision. For system operators investments derived from incentives provided by the regulatory framework (i.e. *UK- Utilities Act*, *Norwegian Energy Act*); these entities were legally bounded to support and to facilitate a market-oriented electricity sector through the development and the maintenance of an economically and technically efficient distribution system [20]. A series of shortcomings was associated with system' operators investments in networks. First, limitations emerged as pertaining to the financial vehicle used in financing these investments, often done by revenues and less through raising debt [21]. Second, investments made by regulated monopolies gave little space and stimulus for innovation and research activities to develop [15] and often were questionable

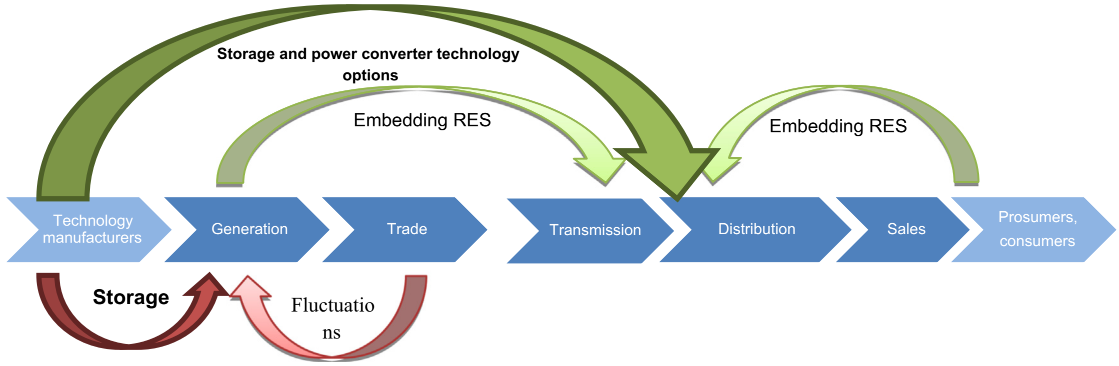

Fig. 1. Indicative representation of network flexibilisation through storage and grid investments required by renewable energy integration in the electricity value chain. Arrows in red represent the need for flexibilisation of the network (storage) resulting from balancing fluctuations in the network generated by the supply (i.e. intermittent sources) and demand (i.e seasonalities). Arrows in green represent the need for flexibilisation of the network (storage or grids) enabling a higher integration of RES in electricity network. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

with respect to their effectiveness in driving the investments that modernize the grid [15]. Third, system operators could generate suboptimal investments whilst aiming at preserving concentrated and national markets [22].

On the contrary, an investment strategy seeking to increase revenues streams (i.e. of RES firms) would give incentives for firms to invest in new technological solutions that increase the elasticity of supply, such as storage capacities and grids. In case knowledge to develop new solutions would fall outside RES firms' competence domain, an intense cooperation process with engineering firms could be set in place, linking profitability of RES industry and the evolution of network infrastructure.

Concerning the market mechanisms, the liberalization induced additional unbalances in the grid flows to be solved through the exchanges in the reserve markets. System operators (SO) exerted an important role in these markets, being responsible in balancing the fluctuations generated by the supply (i.e. intermittent sources) and demand (i.e seasonalities) [16]. For instance, in excess of supply the SO could either pay consumers to consume more or pay suppliers to produce less, previously referred as acquisition of negative balancing power [16]. In some cases, production peaks were handled with exchanges generating negative profits and in some cases even negative prices for generating companies [23]. From the point of view of maximization of social welfare, the hypothesis of increased investments in the flexibility of the network would imply higher elasticity of supply, but also a decrease in the final price (because of new quantities of zero marginal cost sources).

Finally, an increased participation of RES companies could reduce the financing gap faced by planned investments of the European TSO's. For example, the European Network of Transmission System Operators for electricity (ENTSO-E) identified investments requirements in the order of hundreds of billions (€104 billion) to be spent in the next 10 years for new transmission lines aimed at renewables and new conventional plants, security of supply and market integration [24]. In the case that investments maintain at the same level, the TSO would be able to cover only 47% of the ENTSO-E 10-Year Network Development Plan and 61% of the EC Roadmap scenario [24,25].

Thus, the enlarged participation to investments in the modernization of the electricity system would be the result of synergies amongst different players along the supply chain. Accordingly, a profit maximisation framework (Section 3) represents a reasonable strategy for RES producers, investing in research aiming at the expansion and the flexibility of the network. To this aim, RES producers would follow either a process of vertical integration acquiring new competencies, either they could also tie cooperation with external partners (wind turbine manufacturers, engineering firms), in the case in which the knowledge and skills to connect to the local network remains outside the firms' usual domain [26–28]. For example, focusing on eco-innovators, Hemmelskamp [28] and De Marchi [29] found evidence of the use of external sources of information. This leads to our research hypothesis that accounts for feedbacks and complementarity relationships amongst different players (technologies) along the whole supply chain (Fig. 1). To this end we test statistical associations between the profitability of RES industry (wind and PV) and the grid adequacy, measured also through research investments in electricity grids and storage technology. The association between knowledge in electricity grids/storage and the diffusion of wind and PV technologies suggests research partnerships and possible firm strategies motivated by changes in the firm's inputs. This analysis adds to previous studies on the diffusion of RES system, as it provides insights on the extent to which interconnections with other sectors could further enhance the diffusion of the RES technologies.

3. Model specification: RES market versus network infrastructure

The analysis considered the existence of spatial competition between generators, context in which the network adequacy (see Section 4) represented an important basis for the competitive advantages of RES firms' (e.g. wind or PV generation). The RES firms go through a two-step decision process in which they decide their localization and their production from renewable energy sources (*Wind&PV*). Similarly to Head et al. [18] who structured a locational choice of firms according to the site specific (i) accessibility to production factors as labor and land, we specify in (1) the output of wind and photovoltaic (PV), WPV_i, as a function of the technical progress A, the labour L_i and of site specific factors N_i determining the cost of integrating the RES in the network:

$$\begin{cases} WPV_i = \beta_0(A)(L_i)^{\beta}(N_i)^{\gamma} \\ TC_i = p_L L_i + p_N N_i \end{cases} \tag{1}$$

The first order conditions define further the conditional demand input of labour and network as:

$$L_i = \left(\frac{WPV_i}{A}\frac{p_N}{p_L}\right)^{\frac{1}{\beta+\gamma}} \qquad N_i = \left(\frac{WPV_i}{A}\frac{p_L}{p_N}\right)^{\frac{1}{\beta+\gamma}} \tag{2}$$

In a second step, the firm maximizes future profits from *Wind&PV*, defined in terms of net present value NPV_{it}. This methodological framework has been previously used by studies pertaining to technological diffusions [17,30] describing a process in which the net present value from *Wind&PV* production NPV_{it} is maximized under a total cost TC_{it} obtained from Eqs. (1) and (2).

NPV_{it} takes the following functional form:

$$NPV_{it} = \alpha_0 (WPV_{it})^{\alpha_1} \left(\int_0^T P_{it}^{Ft} e^{-rt}\, dt \right)^{\alpha_2} \left(\int_0^T P_{it}^{Coal} e^{-rt}\, dt \right)^{\alpha_3}, \tag{3}$$

where t is the period of time and i indicate the $28+2$ European countries[1], P_{it}^{FT} represents the Feed-In-Tariffs ,P_{it}^{Coal} represents the price of coal. TC_{it} represents the total cost resulting from production of WPV_{it}. Introducing (2) into (1) and in the context of profit maximization (3) we obtain:

$$\alpha_0\alpha_1 (WPV_{it})^{\alpha_1 - 1} \left(P_{it}^{FT}\right)^{\alpha_2} \left(P_{it}^{Coal}\right)^{\alpha_3} = \frac{A^{-1}}{(\beta+\gamma)} (WPV_{it})^{\frac{1}{\beta+\gamma}-1} \left[p_L \left(\frac{L_{it}}{N_{it}}\right)^{\frac{1}{\beta+\gamma}} + p_N \left(\frac{N_{it}}{L_{it}}\right)^{\frac{1}{\beta+\gamma}} \right] \tag{4}$$

After simplifications and putting in logarithmic scale and at time $t = 2011$

$$N_i = f(A, WPV_i, P_i^{FT}, P_i^{Coal}, L_i) \tag{5}$$

where N_i represents the attributes of a local network linked to a set economic indicators giving the profitability of RES activities developed at location i. According to (5) the outcome of the RES diffusion should be set out by the evolution of the network condition, N_i that could embrace a multidimensional definition, and comprised from indicators which describe conditions influencing the cost of access to electricity networks, such as network size, RES losses, research investments in electricity grids and research investments in storage technology.

The degree of association between two sets of indicators, the RES market and electricity networks, are further examined within a canonical framework. This method [31] finds dependencies between the two random vectors X(x_1,x_2…,x_n) and Y(y_1,y_2…,y_m) , so as to maximize the correlations on the dimension of the subspace d_zd$_z$ < min (d_x, d_y) [32]. The canonical correlation can be calculated using the general eigenvalue problem, with a set of linear combinations named U and V for which

$$\mathrm{var}(U_i) = \sum_{k=1}^{n} \sum_{l=1}^{m} a_{ik} a_{il} \mathrm{cov}(X_k, X_l); \quad \mathrm{var}(V_j) = \sum_{k=1}^{n} \sum_{l=1}^{m} b_{jk} b_{jl} \mathrm{cov}(Y_k, Y_l)$$

Coefficients $a_{ik}b_{jl}$ are to be selected so as to maximize the canonical correlation of the canonical pairs $\rho_j = \frac{\mathrm{cov}(U_i V_j)}{\sqrt{\mathrm{var}(V_j)\mathrm{var}(U_i)}}$.

The advantage of using the canonical correlations analysis pertained to a simultaneous comparison of the two sets of indicators over a multiple regressions framework. Its use avoided the need for controlling the circular causality between network and *Wind&PV* market, such as the one deriving from the fact that higher investments in research in infrastructure could insure higher flexibility of the network and hence higher penetration of renewable sources, which give basis for higher research in power networks.

The canonical correlation framework informed upon the degree of association between the two sets of indicators, for which one could originally imagine 2 possible outcomes. On one side the two vectors, i.e. market and network, could be very different, in which case one could signal a disconnection between the profitability of RES industry and network localization. Oppositely, a positive strong correlation between the two indicators might be observed and thus indicating that network increases with growth of RES related activities. This is expected to occur when part of turnover is allocated to investments into the network, allowing further increases in volumes of production to be transmitted into the network. In order to make this argumentation, we use the indicators described in Section 4.

[1] The choice of countries reflects the 28 European member states , plus Norway and Switzerland

4. Materials and data considerations

The adequacy of the power grid is substantially a multi-dimensional and composite concept. It may ideally include a large group of indicators of physical properties (e.g. resilience, robustness, flexibility) that have a well-established theoretical foundation. Although regional case studies offer measurements of such properties within segments of the infrastructure, the construction of a complete harmonized data set for cross country comparisons of network remains an open challenge. We opted for setting out a group of simplified indicators that approximate some dimensions of the power grid adequacy at a country wide level. The first of them measures the size of the network. We expect these indicators would reflect the intensity of the local demand: a higher local demand would translate into a greater need to enhance the transmission capacity. For the present analysis we considered the length of the electricity network through the data made available by ENTSO-E (Table 1).

The second network indicator approximated the losses of RES production arising from infrastructural bottlenecks that restrict the use of available wind or solar power. Calculated as a ratio between the wind curtailment and the total electricity production available for the consumption of a country, this measure aimed at representing the pressure of RES over the entire system. Such an evaluation could provide an important insight on the need of the network to increase its flexibility, which in turn creates an important foundation for further legitimation of the RES technology. Wind curtailment indicator was constructed assuming the average wind capacity factor of 0.25, as the one indicated by [33]. For northern countries, the calculus of wind curtailment used a higher capacity factor of the UK of 0.299 [34]. [2]

In addition to the physical metrics addressing the size and the pressures on the network, we provided two financial indicators estimating the flexibility introduced through innovation activities in: electricity grids and storage technologies. The corporate R&D expenditures, referring to 2011 was estimated using the following bottom-up approach [35–37]. First, the R&D expenditures and technology specific patents were collected at company level. Secondly, in the case of multi technology companies, technology specific R&D investment, accounting for the delay between the occurrence of the research and the filling of the patent application, was allocated following previous studies [36,38] :

$$Corporate\_R\&D_{mkt} = \frac{Patents\_m_{k,t+1}}{Total\_Patents_{k,t+1}} * \mathrm{Research\_expenditures}_{kt}$$

Where m is the specific technology (electricity grids/storage), k is the company and t is time. Third, an average research investment/patent was computed and enabled to include additional companies into the assessment. In some occasions, information about companies' employees in a particular technology allowed further inferences on corporate R&D, following the approach of JRC 2009 [35]. Finally, national/European grid projects were inventoried [39] and further disclosed the amount spent by corporations in research activities in these particular technologies. The summation of corporate R&D investment per technology from all identified companies allowed the approximation of corporate research investments per technology across European countries. Appendix A explains synthetically the steps followed

[2] Capacity factor of 0.299 for UK calculated by DECC (Department of Energy and Climate Change). The same capacity factors was extended for other northern countries such as Denmark, Finland, Ireland, Latvia, Lithuania and also Portugal.

Table 1
Data sources for variables included into the analysis.

Network indicators	
Corporate R&D in grid technologies	*Own elaboration using grid database (26),EPO, Industrial scoreboard and companies' Annual reports*
Corporate R&D in storages 2011	*Own elaboration using grid database (26),EPO, Industrial scoreboard and companies' Annual reports*
Wind curtailment	*Estimated using capacity factor of Technology Map 2013, Wind power database*
Km of lines	*Entso-E, Platts database*
Market Indicators	
Turnover of the wind and PV sector	http://observer.cartajour-online.com
Wind installed capacity	*Wind power database* http://www.thewindpower.net/country_europe_en.php
PV installed capacity	*Epia, 18, Global Market Outlook For Photovoltaics 2013–2017*
Market share of the largest generator in the electricity market - annual data	*Eurostat [nrg_ind_331a]*
Number of companies generating electricity	*Eurostat, Market share of the largest generator in the electricity market*, http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/documents/CIelectricity2011.pdf
Feed in prices PV	*Renewable energy policy. Country profiles*, http://www.reshaping-res-policy.eu/downloads/RE-SHAPING_Renewable-Energy-Policy-Country-profiles-2011_FINAL_1.pdf
Feed in prices wind	*Renewable energy policy. Country profiles*, http://www.reshaping-res-policy.eu/downloads/RE-SHAPING_Renewable-Energy-Policy-Country-profiles-2011_FINAL_1.pdf

in the identification of the companies, the allocation of investments and calibration of results when several indicators were possible to be computed [35].

Market indicators refer mainly to the intensity of diffusion of wind and solar technologies. Whereas a variety of indicators are periodically published by European statistical offices (Table 1), information pertaining the level of Feed-in Tariffs (FiT) remained the objective of particular European projects. Data on FiT were originally represented as ranges of values, as higher forms of public support were given to devices high-integrated into urban structures, while lower values of subsidies were given to ground mounted system. Median values of FiT have been calculated at country level and used for the purposes of the analysis. Zero values have been assumed for countries without FiT tariffs programs, i.e. the ones using the quota system. A null value was attributed for corporate research investment in the case in which it was not possible the identification local private firms' involvement in research activities, such as patenting activities or participation to national/European research projects.

5. European landscape of participants in power supply chain

The ongoing process of liberalization of power markets in the EU area has gradually allowed both *horizontal* and *vertical fragmentation* of the supply chain. The *horizontal fragmentation* process enabled a specialization in specific segments of the supply chain, as in the case of power generation. The horizontal restructuring of the power generation segment translated into a high number of participants in the segment of generation of electricity (an overview for the EU is presented in Fig. 2). Despite the growing number of companies in this segment, the power generation remained in 2011 a rather centralised economic activity across European countries, with an average share of the largest generator in the electricity market of 56%. The level of decentralization was not evenly distributed: Germany, Denmark, Finland, Italy, Lithuania, Norway, Poland, Romania and Spain exhibited more contendible markets. The penetration of RES in the electricity mix and the liberalization of power markets appeared as intertwined evolving processes[3], whose speed was determined for a large part by technological advancement. Economic operators within a specific segment of the power supply chain stimulated innovation activities to foster their competitiveness, investing at the same time on a portfolio of research and development activities targeting technologies out of their core activity. This linkage was suggested occurring both in a downstream direction (manufacturers of RES power generators stimulating the technological progress of grids) as well as toward the upstream in a lesser extent (DSO investing in research in wind and PV generators). A denser distribution network was noted in high RES diffusion countries such as Germany, Switzerland (with more than 800 DSO companies), followed by Spain (349) and France, Norway, Poland and Austria. Furthermore, a high correlation was observed between the number of DSO's and number of companies investing in wind, solar (0.59) and with companies investing in electricity grids and storage technologies (0.74). Additionally, the intensity of the relationship was significant in countries such as Germany, France, Italy and Spain that also revealed a high intensity of diffusion and research activities in *Wind&PV* [41]. Scrutinizing the players investing in research activities in electricity grids and storage provides further insights. Interestingly enough, the contribution of wind energy companies originates from the need to handle the local impacts of integration in the power grid, e.g. the changes in branch flows, the altered voltage levels, the increased fault currents and the risk of electrical islanding [40].

The corporate research investments in electricity grids technology[4] (estimated to EUR 249 million in 2011) revealed a geographic concentration in high RES diffusion countries such as Germany, Switzerland, UK, France, Denmark and Spain. These investments were initiated by companies specialized in *Automation &Power Technologies* or *Electronic &Electrical Equipment*; some of the firms were also involved developing renewable energy technologies (Siemens and ABB). The sampled TSO's accounted for 1% of corporate research investment, whereas utilities invested four times more than the TSO's. Altogether generating energy companies accounted for 30% of investments, out of which *wind* turbine manufacturers accounted for nearly 10%, *solar* manufacturers accounted 7% and *oil, gas and nuclear* together only 3%. Overall, a non-negligible contribution is exerted by RES technology manufacturers in research activities in electricity grids.

The corporate research investment in storage technology was estimated to EUR 1514 million in 2011[5]. It concentrated in one technology (batteries, 89 % of corporate research) and over two countries (Germany and France). The non-battery technology, gathered EUR 171 million (own calculations) and referred to the development of advanced capacitors, thermal storage, pressurized fluid storage, mechanical energy storage and pumped hydro storage. Companies originating from *automotive&automation, energy, transport and defense* invested significantly in mechanical storage.

[3] A correlation analysis on this shows a statistically significant value of 0.36 of the Pearson correlation coefficient between the market fragmentation (average size of non-incumbent suppliers) and the penetration of RES (installed capacities).

[4] Defined as technologies for an efficient electrical power generation, transmission or distribution Y02E40 (including subgroups) but also power conversion electric or electronic aspects for wind Y02E10/76 and Solar technologies Y02E10/56

[5] own calculations [55].

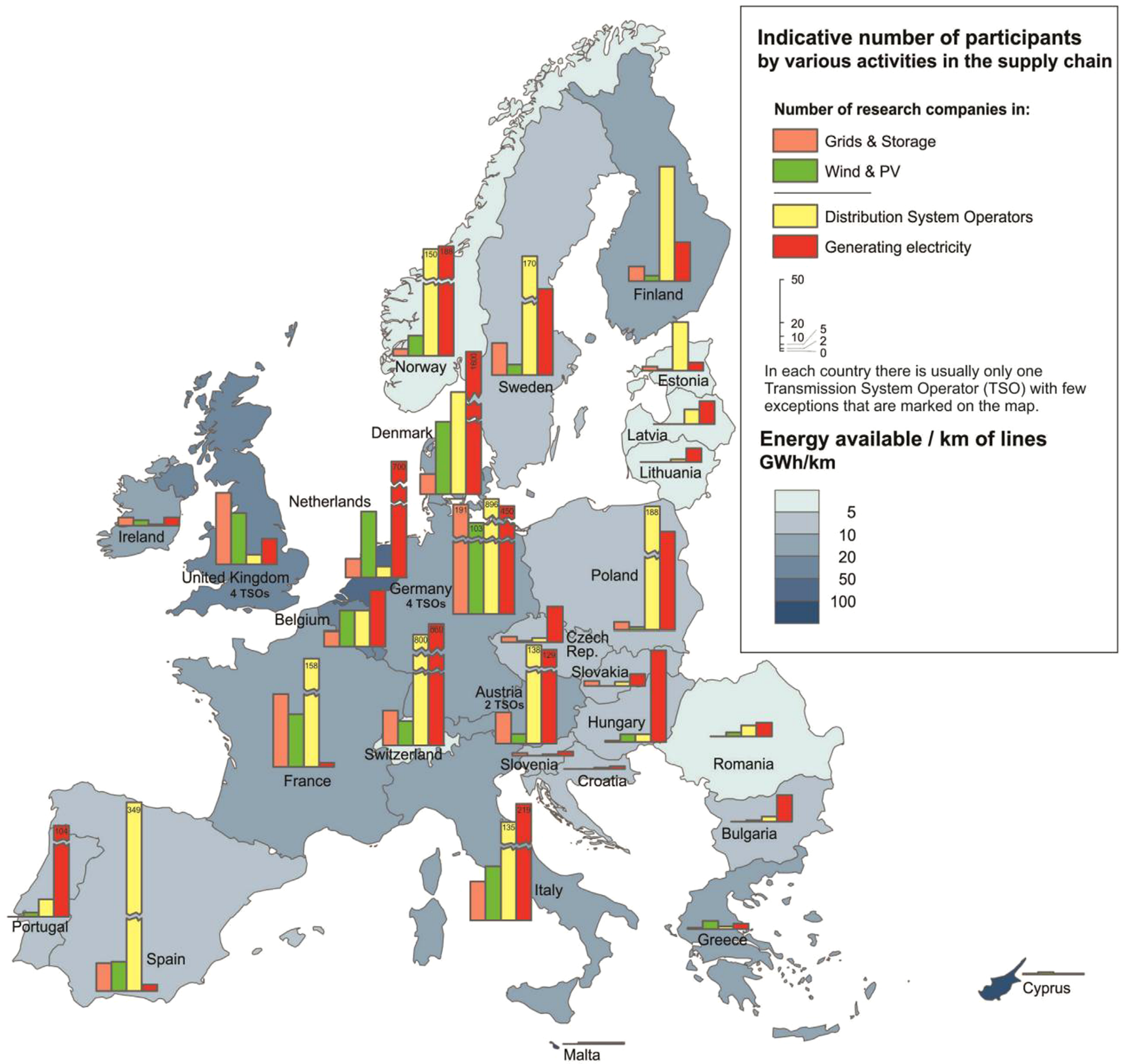

Fig. 2. Map representing the composition of the supply chain. The intensity of the color of countries describes the total electricity for consumption that has to be transported over the transmission lines (data source Platts, ENTSO-E). Number of DSO's was collected from Eurelectric (2010), the number of companies generating electricity was collected from Eurostat. The number of companies investing in research activities for wind energy, solar energy, electricity grids and storage technology results from our own elaboration according to methodology and data sources presented in Section 4.

Industrial engineering firms, utility and energy companies accounted for a large share of European pumped hydro storage research investments. Corporate research investments in ultra/supercapacitors were mainly realized by companies having a specialization in *Chemical, Industrial, Metals&Mining* and *Automobile& Parts*.

Although lesser obvious was the involvement of RES technology manufacturers in the development of storage technologies, cooperation with external partners (engineering firms), could be a valid strategy to handle knowledge and skills that fall outside the firms' usual domain. Conversely, RES involvement in electricity grids technology supports our intuition that an organizational integration of knowledge creation was actually taking the place of the previous forms of vertical integration of economic activities within the power supply chain Figs 3 and 4.

6. Results: associations between RES market and network infrastructure

The vertical changes in the supply chain, accompanying the diffusion of the RES and the modernization of the network, were examined by the help of canonical correlation based analysis. The method compared and identified the degree of association between two sets of variables, i.e RES market and electricity network (see Section 4, summarized in Appendix B). This association was tested separately for the wind sector, for the PV sector, as well for the two sectors considered together. An appraisal of these 3 full canonical models was based on tests over the shared variance between the predictor and criterion variables across all of the canonical functions [42]. All the multivariate tests rejected the null hypothesis that there was no relationship between the variable sets i.e., the *Wind&PV*

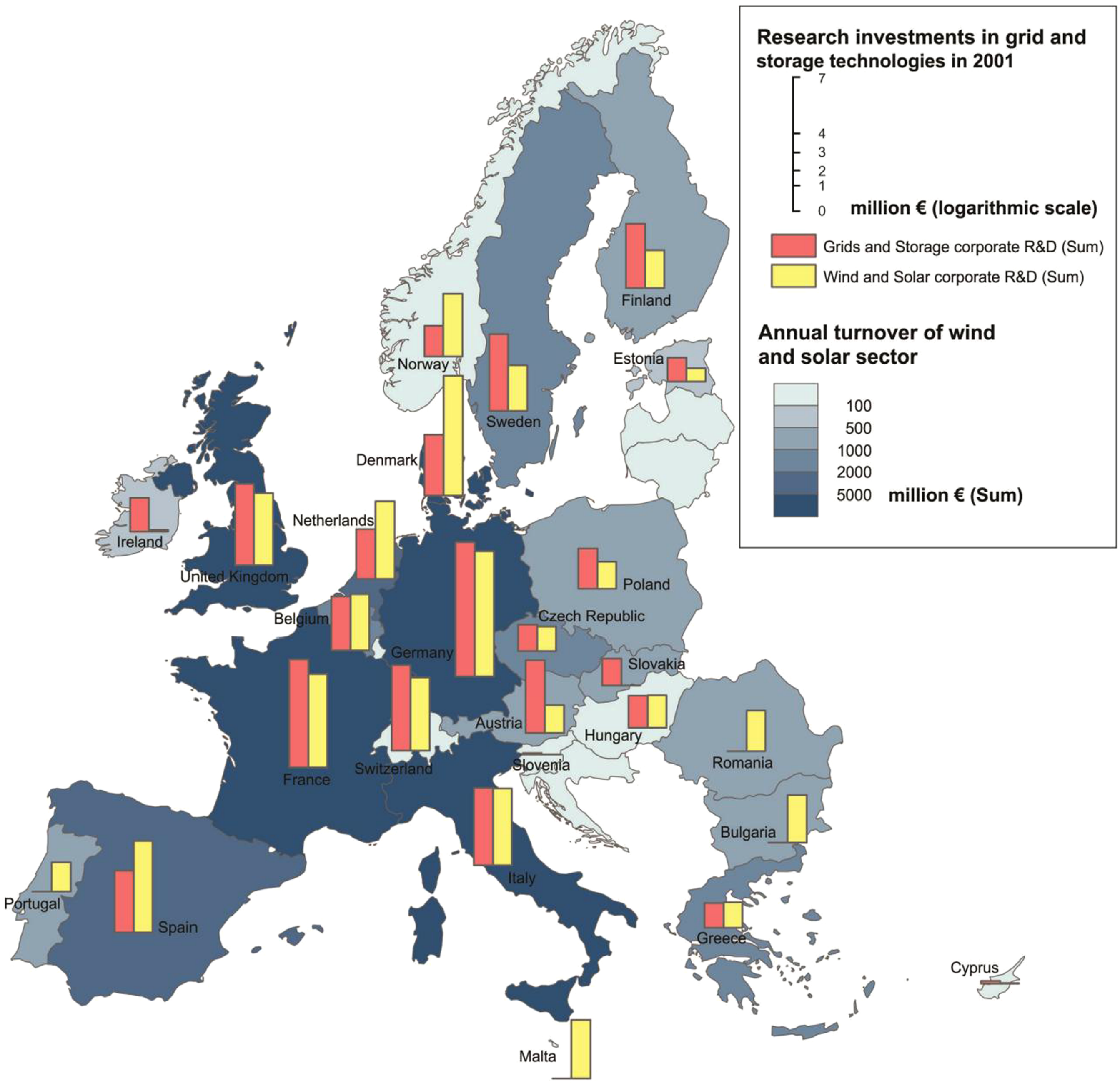

Fig. 3. Geographic distribution of corporate research investments in electricity grids and storage technologies (in red) versus the corporate research investments in wind and solar technologies (in yellow). The data is estimated using the methodology described in Section 4. The year of the assessment is 2011. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

market indicators and the network infrastructure (Appendix C). Furthermore, running significance tests on the first and second canonical correlation we noticed that only the first function remained significant (and represented in Figs. 5–7). For the aggregated model (*Wind&PV* together) the first canonical function maximizing the Pearson canonical correlation between the two synthetic variables explained 91% of the variance, whilst only 87% for the PV model and 89% for the wind model. Figs. 5–7 and Appendix D1–D3 present the contribution of market and network indicators to the canonical function, and their level of representativeness for the model function of the percentage of shared variance between the observed variable and the synthetic variable created from the observed variable's set.

A significant and positive association was found between the wind market and power network indicators (Fig. 5). The most significant variables explaining this association relate to wind installed capacities and corporate research investments. Interestingly, the wind installed capacities were positively associated with network capacity in terms of km lines of transmission. Confirming these results one can mention the plan of expansion and upgrading of the network traced by the 4 German TSO's facing in the next decade both accelerated diffusion of wind technology and nuclear decommissioning. Such modification of the energy system claimed additional investments (€20 billion by 2022) for upgrading 4400 km of existing transmission lines, and additional 3800 km of new high-voltage lines; additional expansion of the wind power on the North and Baltic Seas would cost another €12 billion [12].

Overall, the variety of significant network indicators potentially enabling wind market further revealed the complexity of aspects needed to be taken into account for its integration, i.e. transmission “bottlenecks”, communication between different grids, wind energy deficits between wind and calm days [43], forecasting errors [44]. The multi

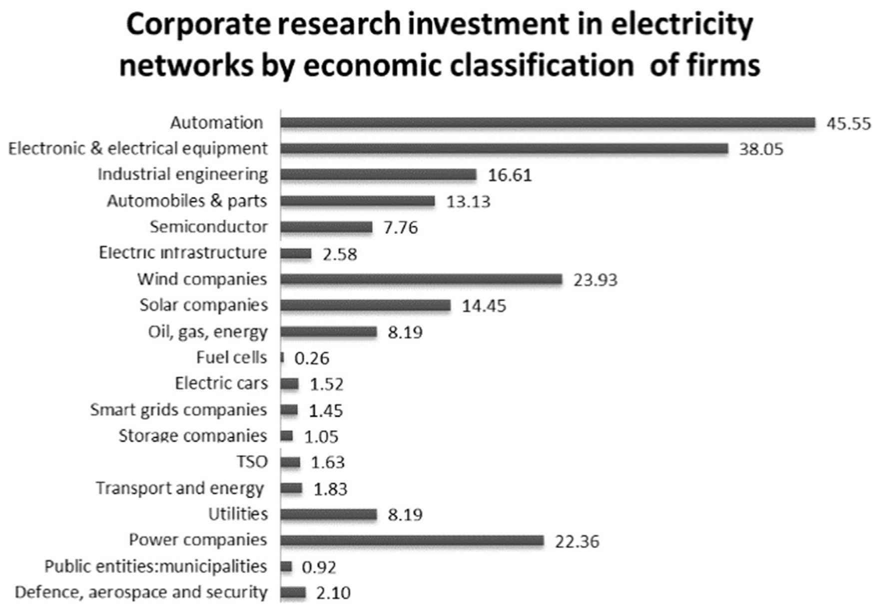

Fig. 4. Corporate R&D investments in electricity grids by sector of activity of companies involved in such activities. The year of assessment – 2011. Own elaboration [55].

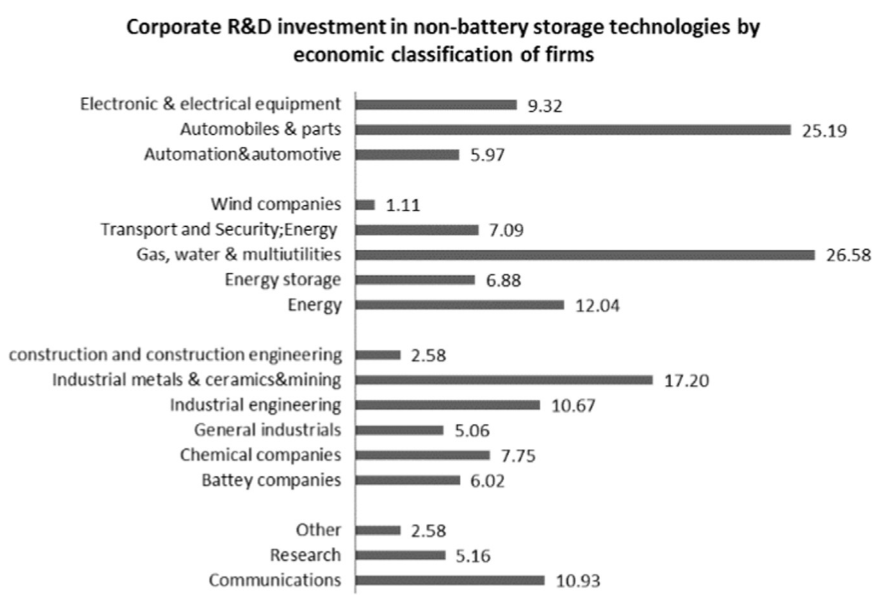

Fig. 5. Corporate R&D investments in storage technology by sector of activity of companies involved in such activities. The year of assessment – 2011. Own elaboration.

facet aspect of these problems might require specific technological solutions linked to network reliability (network length, pressure over the network) and network flexibility. Storage devices are advanced as solutions treating specific problems [45]: flywheels, capacitors and batteries were considered as the most suitable maintaining power quality and grid stability applications; Sodium–sulfur batteries were considered as a potentially faster cost effective solution; pumped hydro storage were considered as a suitable timescale trade-offs; and compressed air energy storage and flow batteries were considered as seasonal storage solution. The diversity of problems related to wind integration would invite both technology specific skills (i.e. wind manufacturers) as well as interdisciplinary skills (automation, electric companies) to invest in options, whilst enabling further RES manufacturers to benefit from linkage economies. Moreover, the hypothesis that increased cooperation and reliance on external sources of information of the firms could further help the diffusion of RES.

An analysis of diffusion enablers for PV technology provided useful insight: the PV installed capacities were positively and significantly associated only with investments in *storage technologies* (Fig. 6). Although there is no affordable storage battery large enough to store all the surplus energy on the grid [46], there are studies showing that for stand-alone PV applications, or specific grid-connected applications batteries can already represent a cost-effective solution [47]. In fact, from various forms of energy storage, i.e. mechanical, electric or chemical, batteries were the most vastly used energy storage option for renewable energy sources, such as photovoltaic [47–49]. In a localized context, a new form of creating value can be legitimized and originated in the significant association between PV diffusion by storage technologies. A business model coupling storage devices with PV technology could implement adjustments needed in order to fit the existing system to the intermittent renewable energy technology.

Finally, the joint *Wind&PV* market revealed to be significantly correlated with research in electricity grids and storage technologies. The deployment subsidies (FiT), previously testified as being effective in inducing mass scale production [17] demonstrated a not

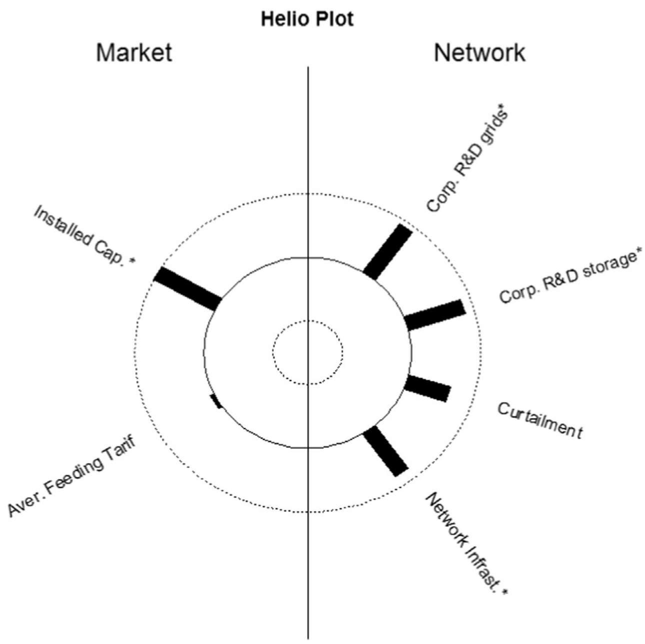

Fig. 6. Graphical representation of the association between wind market indicators and network indicators. Only the first canonical function was retained as being the most significant. Significant variables, for which communality coefficients are greater than |0.45| bear an asterisk.

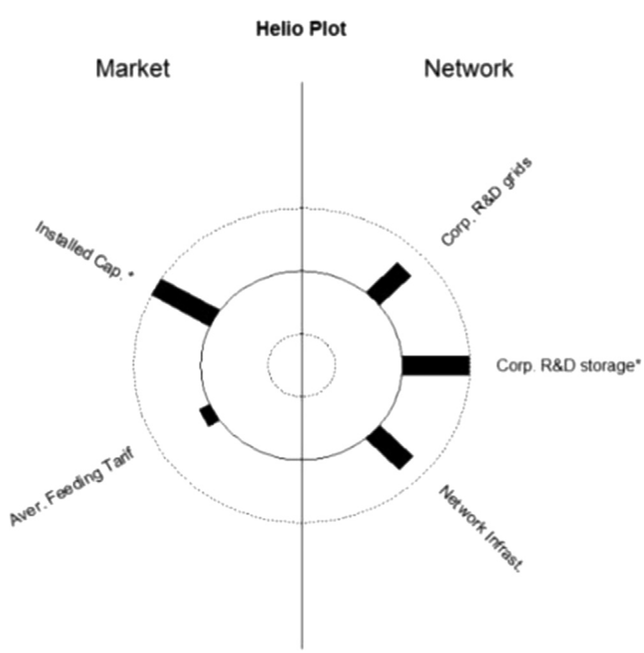

Fig. 7. Graphical representation of the association of PV market indicators and network indicators. Only the first canonical function was retained as being the most significant. Significant variables, for which communality coefficients are greater than |0.45| bear an asterisk.

significant contribution to association between market and network. An examination of the correlation matrix revealed for both wind and PV sector a weak correlation between the level of FiT and the research investment in electricity grids and storage. This result supports the argument that FiT measures had a limited role to support RES integration in energy system, in particular with respect to inducing research activities enabling network flexibilization (see Appendix E).

7. Discussion of the results

This paper adds to the discussion carried around the integration of renewable energy sources and identifies two major enablers of higher integration of RES, i.e. research in electricity grids and storage. Our economic analysis converges to conclusions previously set out by engineering studies [50,51] stating that the presence of energy storage devices is likely to increase RES dispatchability. The contribution of these enabling technologies to the development of RES market potentially suggests business models that couple the two dimensions (RES and power network). The viability of such options remains a challenge because of the high costs the storage solutions add to the already expensive RES and electricity networks [52].

Public support for the development of storage and grids technologies could help the reduction of costs for energy storage and further accelerate RES diffusion. The enhanced availability of RES in the system requires that research efforts should be further complemented by public intervention in a context in which deployment measures (the FiT) play a limited role in explaining the association between RES market and power network (see Figs. 6–8). A joint examination of the corporate and public research for *Wind&PV*, as well as for electricity grids and storage show that the public support for research in electricity grids and storage represented only a half of what was dedicated for research activities in wind and solar across European countries. The imbalances grow when scrutinizing modernization of the network: whilst public support for electricity grids (IEA database) was comparable to our estimated private investment, the public support for research in storage technology[6] was four times smaller than private research investment in only non-battery technology. A serious imbalance could be envisaged between plans for RES generation and the infrastructure needed to integrate these sources. Furthermore, imbalances might grow considering the anticipated changes generated by decommissioning plans. This finding triggers additional concerns under low level of the research subsidies for renewable technologies, in comparison to the cost of pull subsidies. For example, for every Euro spent on research subsidies, additional € 35 to € 41 are spent on the deployment of existing technologies [53]. A successful renewable technology policy could aim at reducing the degree of imbalances between supply-push and demand-pull measures for a specific power technology, whilst supporting research aiming at developing the infrastructure needed to integrate these sources. The slow alignment of public institutions with practices and realities of other sectors could hamper the further diffusion of renewable energy technologies and therefore need additional attention from other system actors that have an interest in speeding up the diffusion of renewable energy [54].

The RES technology manufacturers were identified as investors in the modernization of the electricity network through research activities such as those related to electricity grids and storage. Their participation could relieve one of the important systemic weaknesses, i.e. the suboptimal of physical infrastructure blocking the operation and the development of RES innovation systems. An important role in the transformation of energy systems can be enabled outside the traditional approach, in which investment decision for capacity transmission can be decoupled by spatial aspects [14]. Rather RES diffusion is further enabled through storage options, the latter depending on the target services required and the location on the grid [52]. As the locational component is important for firms seeking maximization of profit, the public incentives could be redesigned in order to help further diversification of research portfolios and to address the flexibilisation of power networks.

Nevertheless this represents only one facet of the numerous solutions that could be proposed as viable options for the transition to an

[6] The analysis does not include nor for private or public part investments in hydrogen and fuel cells

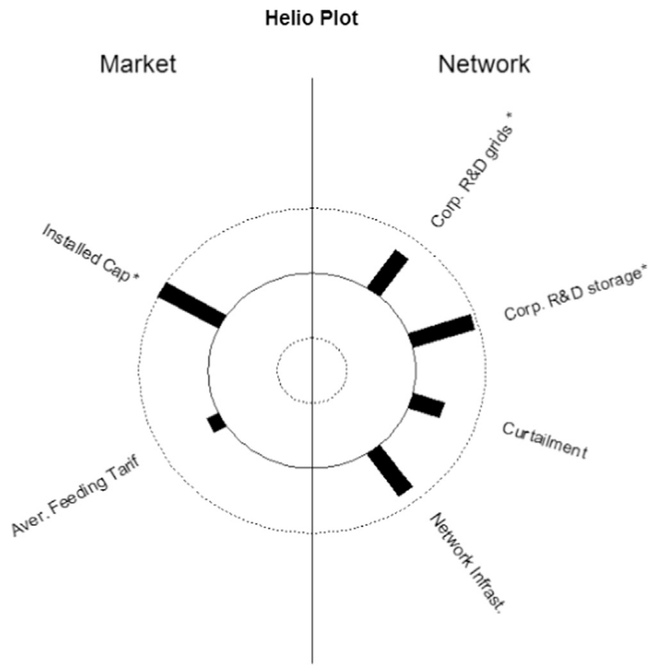

Fig. 8. Graphical representation of the association of wind&PV market indicators and network indicators. Star represent the representative values selected with commonalities coefficients higher than 0.45, i.e. explaining more than 45% of variance on the canonical function. Only the first canonical function was retained as being the most significant.

economy incorporating higher renewables. Other system actors, such as municipalities, energy communities could be mobilized in attracting resources for the diffusion of the renewables [56]. Also utility companies and their ability to manage variable renewable power output [57,58] could further overcome through demand response strategies the structural challenges induced by the growth of renewable generation in the electricity system.

8. Conclusion

Transition to low carbon economy induced changes in electricity market, changes related to its structure and mechanism. We examined the case of variable renewable energy sources (wind&PV) participating to these changes, and provided evidence over a specific category of investors recently active in modernization of power networks, i.e the RES technology manufacturers. In the short run their rationale of investment relies in network flexibilization, as means of obtaining higher returns from RES activities. Additional opportunities for development and profits from mid-term development of the market derive from expansion in value chain activities, yielding economies of scope and linkage economies. Apart the advantages that the storage & grid solutions would have for further RES diffusion, one could imagine that the opposite is also true: a coupled RES and storage system could help the latter in bringing down their cost. A win–win situation can be signaled, and the present analysis provided useful insights on associations between RES market and network infrastructure. First, policy measures such as deployment subsidies (FiT) had a limited role in supporting RES integration in energy system, in particular with respect to inducing research activities enabling network flexibilization. Secondly, both *Wind&PV* market showed a high sensitivity to research in electricity grids and storage. If the uninterrupted availability of RES in the system requires further research efforts, one could further investigate whether a policy focusing only on deployment is sufficiently ready to meet the changes occurring and the future constraints of higher weight of intermittent sources in the energy system. The convergence of interests among wind and PV technology suppliers emerging by the present analyzes supports the idea that relevant complementarities and interactions are already in place. The industrial, climate and energy policies that are dealing with such complexity should thus be inspired according to a systemic perspective. Some relevant policy document are already confirming this view [59] and a future stream of research should expand the empirical analysis of such interactions.

Conflict of interests

With the here present letter I confirm that the present publication has no conflict of interest arising out of my author representation in the submission described herein.

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Disclaimer

The information and views set out in this article are those of the authors and do not necessarily reflect the official opinion of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

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Appendix A.

See Fig A1.

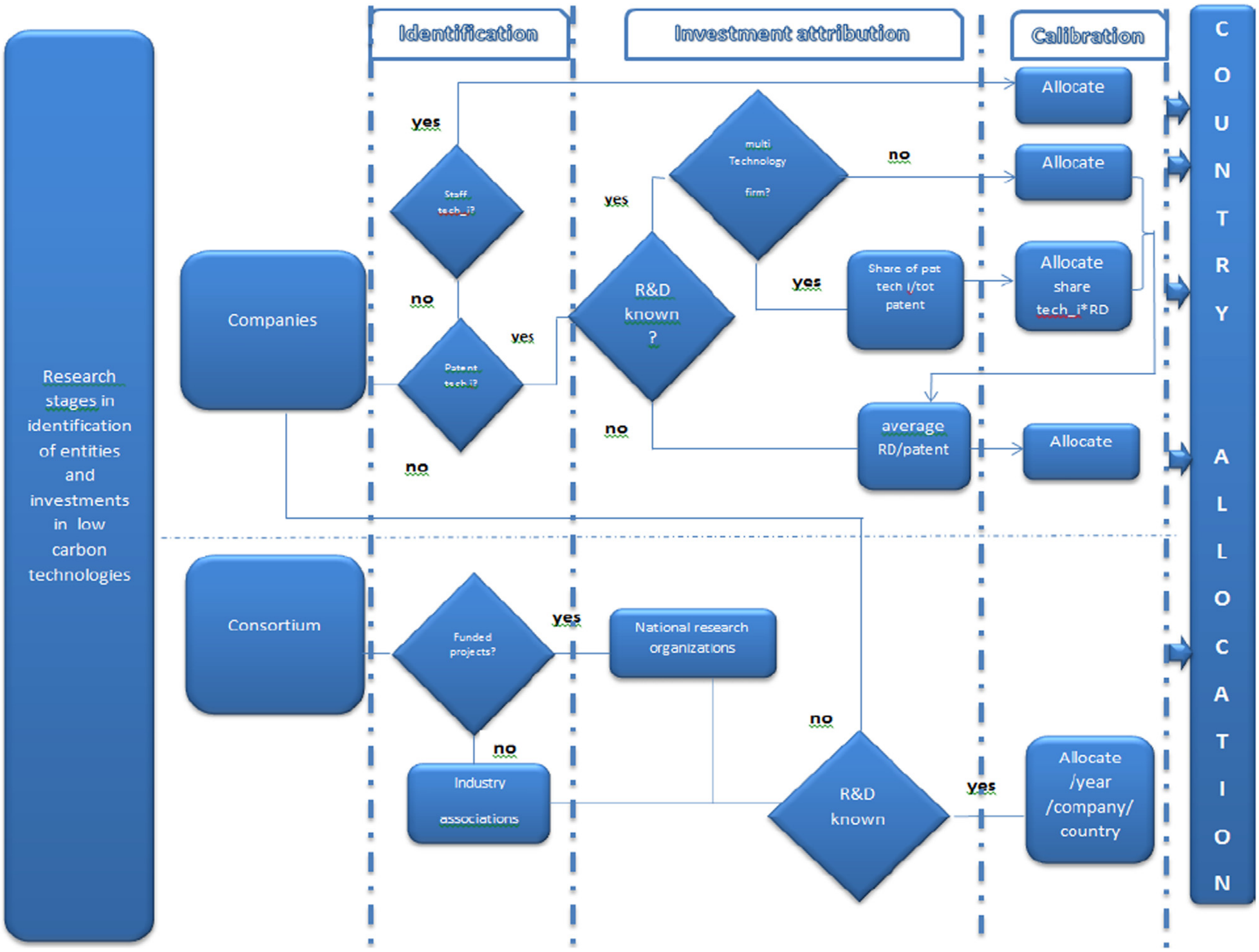


Fig. A1. Identification procedure of companies investing in low carbon energy technologies.

Appendix B

See Table B1.

Table B1
2 Descriptive statistics of model variables.

	Installed PV capacities (GW)	Installed wind capacities (GW)	Average country Fit for PV (100 Eur/MW)	Average country Fit for wind (100 Eur/MW)	Corporate research investment in grid technology (EUR 100 millions)	Corporate research investment in storage technology (EUR 100 millions)	Network lines length (thousands of km)
Min.	0	0	0	0	0	0	0.00173
1st Qu.	0.00325	0.1452	0	0.5434	0	0	1.99792
Median	0.0707	0.751	2.11	0.7675	0.01359	0.0344	3.94457
Mean	1.75584	3.1516	1.799	0.7646	0.08315	0.5026	8.18292
3rd Qu.	0.595	2.7622	3.087	0.9455	0.09259	0.1846	8.78218
Max.	24.807	29.06	5.5	2.2	0.51052	9.8301	39.58655

Appendix C

See Table C1.

Table C1
Statistical significance of the association between the network and market variables.

PV					
	Statistic	***df1***	***df2***	***F***	**Prob > *F***
Wilks' lambda	0.205	6	50	10.055	0.0000 e
Pillai's trace	0.807	6	52	5.873	0.0001 a
Lawley-Hotelling trace	3.807	6	48	15.220	0.0000 a
Roy's largest root	3.788	3	26	32.829	0.0000 u
Wind					
	Statistic	***df1***	***df2***	***F***	**Prob > *F***
Wilks' lambda	0.195	8	48	7.552	0.0000 e
Pillai's trace	0.863	8	50	4.753	0.0002 a
Lawley–Hotelling trace	3.796	8	46	10.913	0.0000 a
Roy's largest root	3.713	4	25	23.212	0.0000 u
Wind&PV					
	Statistic	***df1***	***df2***	***F***	**Prob > *F***
Wilks' lambda	0.151	8	48	9.419	0.0000 e
Pillai's trace	0.900	8	50	5.121	0.0001 a
Lawley–Hotelling trace	5.260	8	46	15.122	0.0000 a
Roy's largest root	5.193	4	25	32.461	0.0000 u

Appendix D

See Table D.1, Table D2 and Table D3.

Table D.1
Wind market and network variables. Raw coefficients, (Squared) correlation with canonical functions (%)Only the first function is shown, as being the only significant one.

	Raw coefficients	***Correlation with canonical functions***	***Squared Correlation with canonical functions (%)***
RES market indicators			
Wind installed capacities	0.154	0.887	0.786769
FiT for wind energy	0.026	0.014	0.000196
Network indicators			
Network length	0.0366	0.765	0.585225
Corporate research in electricity grids	1.199	0.655	0.429025
Corporate research in storage technologies	16.858	0.775	0.600625
Share wind curtailment in total electricity available for consumption	0.047	0.435	0.189225

Table D2
PV market and network variables. Raw coefficients, (Squared) correlation with canonical functions (%).

	Raw coefficients	***Correlation with canonical functions***	***Squared correlation with canonical functions (%)***
RES market indicators			
PV installed capacities	0.202	0.887	0.786
FiT for PV	−0.04	0.157	0.024
Network indicators			
Network length	0.020	0.613	0.375
Corporate research in electricity grids	−0.45	0.587	0.344
Corporate research in storage technologies	0.4956	0.877	0.769

Table D3
Wind&PV and network variables. Raw coefficients, (Squared) correlation with canonical functions (%).

	Raw coefficients	***Correlation with canonical functions***	***Squared correlation with canonical functions (%)***
RES market indicators			
Wind&PV **installed capacities**	0.091	0.915	0.837
Max FiT between wind and PV	−0.024	0.175	0.030
Network indicators			
Network length	0.035	0.731	0.534
Corporate research in electricity grids	0.53	0.654	0.427
Corporate research in storage technologies	0.34	0.857	0.734
Share wind curtailment in total electricity available for consumption	13.04	0.438	0.191

Appendix E. Correlation matrix for matrix and network variables defined as: 1-Installed capacities by specific technology (wind or PV); 2 - Feed in Tariffs by country for specific technology (wind or PV), 3- Corporate research in electricity grids ;4-orporate research in storage technologies;5- Share wind curtailment in total electricity available for consumption ;6-Network Length

See Table E1 and Table E2.

Table E1
Correlation matrix between PV market and network variables.

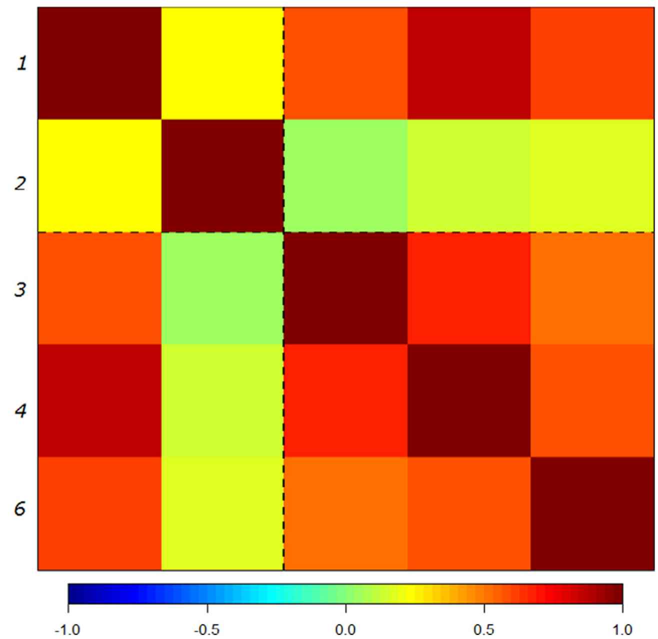
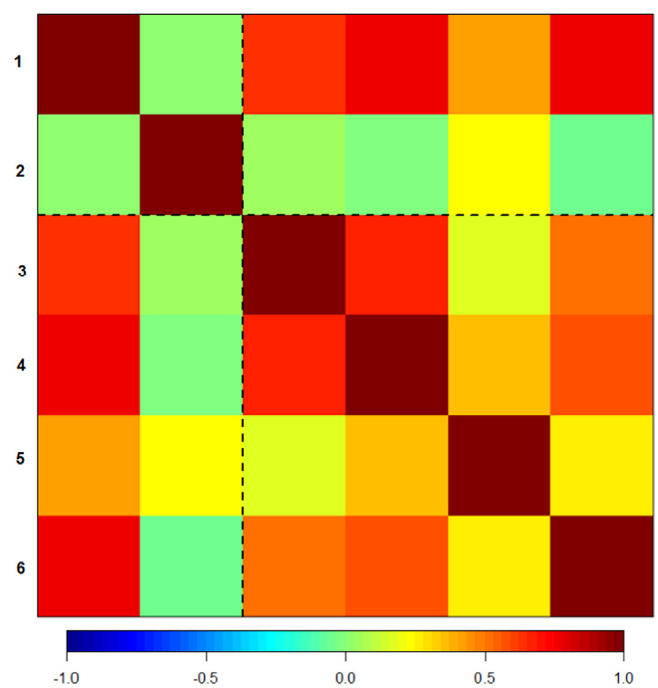


Table E2
Correlation matrix between Wind market and network variables



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